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Room temperature ballistic transport in deeply etched cross-junctions

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Abstract. We measured the transmission in nanoscopic cross-junctions at variable temperature. The devices were prepared by deep etching through a two-dimensional electron gas in InGaAs/InP samples. Our experiments show that the transmission characteristic is partly ballistic even at room temperature. The measurements are analysed in terms of an equivalent network, and the involved resistances are related to the electron mean free path.

Introduction

Nanoscopic cross-junctions are examples for non-classical devices that might have potential for novel applications at the same time as they are subject to very basic research. In a cross-junction an injected electron from one terminal can propagate into each of the remaining three ports or be reflected back to the source. If the size of the junction is smaller or comparable to the electrons mean free path, the probability for straight propagation into the opposite port will be enhanced, i.e. the electrons will propagate ballistically. This leads to nonlinearities in the transmission behavior. In a four-terminal resistance measurement, using the terminals 1–2 for the current source and 3–4 for voltage measurement (see Fig. 1a), a negative differential resistance will be found [1]. The behavior of the junction can be described by means of the conductance matrix $\hat{G}$: $I = \hat{G}U$, where I and U are the column vectors of the incoming currents and the voltages at each terminal, respectively. The conductance matrix can be written down if we apply Kirchhoff's rules on the equivalent network of resistances in Fig. 1b. We suppose that the junction has perfect symmetry. Thus, the two conductances $G_i = 1/R_i$ and $G_o = 1/R_o$ (corresponding to the "inner" straight and the "outer" bend current
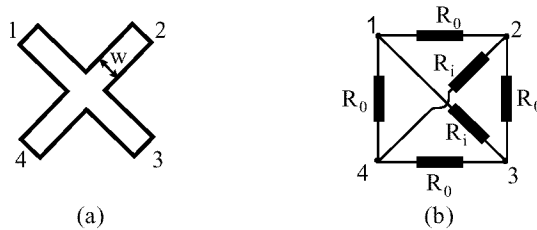

Fig 1. (a) symmetric cross-junction with width w, (b) corresponding network.

paths) can describe the junction. Then we can write:

$$
I = \hat{G}U = \begin{pmatrix} 2G_\mathrm{o} + G_\mathrm{i} & -G_\mathrm{o} & -G_\mathrm{i} & -G_\mathrm{o} \\ -G_\mathrm{o} & 2G_\mathrm{o} + G_\mathrm{i} & -G_\mathrm{o} & -G_\mathrm{i} \\ -G_\mathrm{i} & -G_\mathrm{o} & 2G_\mathrm{o} + G_\mathrm{i} & -G_\mathrm{o} \\ -G_\mathrm{o} & -G_\mathrm{i} & -G_\mathrm{o} & 2G_\mathrm{o} + G_\mathrm{i} \end{pmatrix} U. \tag{1}
$$

For the analysis of our measurements, we rewrite this equation to calculate G_o and G_i from the measured voltages and currents. The comparison between G_o and G_i lets us estimate the degree of ballistic transport in the junction.

1 Sample preparation and measurement details

We have prepared the devices by deep dry etching through a $In_{0.53}Ga_{0.47}As/InP$ two-dimensional electron gas (2DEG). The 2DEGs are grown by MOVPE on InP:Fe substrate. The active layer is a 12 nm thick $In_{0.53}Ga_{0.47}As$ layer, which by a 15 nm InP spacer is separated from the 10 nm thick n-InP doping layer (1×10^{18} cm^{-3} Si). The carrier density in the active layer was determined in Hall measurements in macroscopic Hall bar samples. At $T = 23$ K we obtained a carrier density of $N_{2d} = 3 \times 10^{11}$ cm^{-2} and electron mobility $\mu \approx 8$ m^2/Vs. The mean free path L_0 has been extracted from the Hall measurements. L_0 varies between 700 nm and 150 nm for temperature between 20 K and 293 K, respectively.

To fabricate nanostructures, the samples were patterned by electron beam lithography. We etched through the active layer with CH_4/H_2 reactive ion etching. Ohmic contacts were deposited on the capping InP layer and annealed at 425°C. Details of the sample fabrication are described in [2]. In that paper we demonstrated that this deep dry etching process allows fabrication of high-quality nanostructures, which exhibited quantized conductance at 20 K.

Electrical measurements (cw) have been done at variable temperature with Keithley K2400 source-meter units to source and measure voltages and currents. The contact resistance R_c of our ohmic contacts was determined independently (R_c varies between 1.8 kΩ and 9.5 kΩ when the temperature increases from 77 K to 293 K, respectively) and taken into account in the analysis of the measured data.

2 Results and discussion

The transmission characteristics of our devices were measured by supplying a voltage V_{41} between the terminals 4 and 1 and measuring both the current I_{41} and the voltage difference V_{32} between terminals 3 and 2.

In Fig. 2, V_{41} is plotted versus V_{32} in a 320 nm wide cross-junction for 5 K and room temperature. The ballistic behavior at 5 K can be seen very clearly in the negative derivative dV_{32}/dV_{41}. With increasing magnitude of V_{41} the number of electrons, which propagate ballistically, decreases, thus leading to decreasing magnitude of dV_{32}/dV_{41}. This is mainly due to increasing electron-electron and electron-LO-phonon scattering. For measurement at room temperature, we find that the magnitude of dV_{32}/dV_{41} is strongly reduced and the sign is reversed. This corresponds to the potential difference between port 3 and port 2 created by electrons which underly drift-diffusion transport from port 4 to port 1.
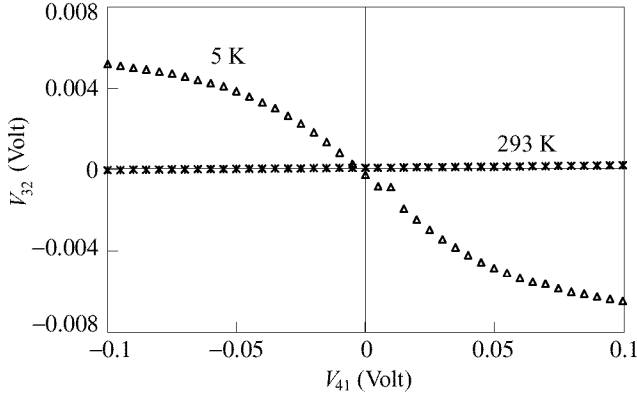
Fig 2. Dependence of V_{32} on V_{41} for a cross with $w = 320$ nm at 5 K and 293 K
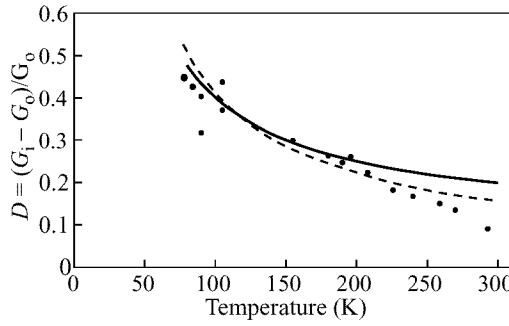

Fig 3. Degree of ballistic transport in a cross-junction with $w = 200$ nm versus temperature. Dots: extracted from the measurements; line: calculated using the model described in the text and the measured $L_0(T)$; dotted line: same as above, but modified with $G_o^c/G_i^c = 1.1$.

For a more detailed analysis we chose a 200 nm wide cross. We measured the dependence of V_{23} and I_{41} on V_{41} between 77 K and 293 K. From the results, G_o and G_i were extracted as described above. Finally their normalized difference $D = (G_i - G_o)/G_o$ was plotted versus the temperature in Fig. 3. We used the values of G_o and G_i at $V_{41} = 0$, where electron-electron interaction should be neglegible.

Qualitatively, the decrease of D with increasing temperature is expected, as higher temperature leads to increasing scattering and decreasing ballistic transport. It is remarkable that in the 200 nm wide cross-junction, even at room temperature a fraction of the electrons propagates ballistically $(D > 0)$. This corresponds to the fact that the mean free path is comparable to the size of the cross.

For a first analysis of the experimental results we chose a purely phenomenological approach. The probability of scattering in a conductor with length L is $P = L/(L + L_0)$ where L_0 is the mean free path of the electrons [3]. Now, we can suppose that we measure an ensemble average for all electrons passing through the cross-junction. Of all electrons injected in one port, we can expect the fractions $(1 - P)$ and P to behave ballistically and as in classical (i.e. macroscopic) conductors, respectively. Let us idealize

the classical case with $G_\mathrm{o}^\mathrm{c} = G_\mathrm{i}^\mathrm{c} = G^\mathrm{c}$ while in the strictly ballistic case $G_\mathrm{o}^\mathrm{b} = 0$, $G_\mathrm{i}^\mathrm{b} \equiv G^\mathrm{b}$. We use P as weight and get for the averaged $G_\mathrm{o}^\mathrm{ave}$, $G_\mathrm{i}^\mathrm{ave}$ the following equation:

$$D^\mathrm{ave} = \frac{G_\mathrm{i}^\mathrm{ave} - G_\mathrm{o}^\mathrm{ave}}{G_\mathrm{o}^\mathrm{eff}} = \frac{1 - P}{P} \frac{G^\mathrm{b}}{G^\mathrm{c}} = \frac{L_0}{L} \frac{G^\mathrm{b}}{G^\mathrm{c}}. \tag{2}$$

This relates our measured D (identified with D^ave) to L_0. Using $G^\mathrm{b}/G^\mathrm{c}$ as adjustable parameter and the measured dependence $L_0(T)$, we get the solid curve in Fig. 3. In general, there is good agreement between both curves. However, at larger temperatures the measured D drops faster than the calculated curve.

To understand this and to improve the agreement, a more detailed analysis is needed than what can be presented here [4]. In particular, a more thorough consideration of the scattering mechanism is required. The probability for an electron to be scattered into a port might not be the same for all ports. Instead, the scattering probability might be slightly larger for the side ports. This means that the calculation overestimates G_i and underestimates G_o with increasing number of scattering events (decreasing L_0 and T). This argument agrees with the observation of Fig. 2 ($dV_{32}/dV_{41} > 0$). The fit is getting much more satisfying if we suppose that $G_\mathrm{o}^\mathrm{c} = 1.1 \cdot G_\mathrm{i}^\mathrm{c}$ (dotted line in Fig. 3). However, more effort is needed to describe the behavior of the electrons in the cross in terms of a scattering matrix, which then can be related to the conductance matrix.

Furthermore, the electrically active width of the cross is likely to be smaller than the lithographically defined one. In a more detailed analysis one could determine the size of the depletion volume near the etched surfaces and estimate the actual size and shape of the confining potential, which probably deviates from the simple cross geometry.

3 Conclusions

To conclude, we presented experiments on the transmission characteristics of nano-scopic cross-junctions. Evidence for ballistic transport was found in a 320 nm wide cross at low temperature and in a 200 nm wide cross even at room temperature. The degree of ballistic transport, decreasing with increasing temperature, was related to the measured electron mean free paths by a simple model.

References

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